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Investigation of the Expansion in InP layer bonded to Si and its Effects on the Performance of the Photonic Crystal Lasers with the Buried Heterostructure

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Integration of III-V materials on silicon platform is an actively sought approach to realize efficient and low energy consumption on-chip light sources for optical interconnects in data processing and communications applications. While high-quality epitaxial growth with low defect-density is very challenging due to large lattice mismatch and different crystal structures of III-V and Si materials, the significant progress of wafer bonding technology makes it a convenient alternative for the large-scale semiconductor materials integration. Typically, wafers are bonded together either by using an intermediate adhesive layer, or directly. In general, the first method relaxes constraints on the required surface smoothness and cleanliness to achieve high bonding yield. On the other hand, the direct wafer bonding is preferred from the device point of view, as the lack of intermediate adhesive layer offers better control of the coupling between the bonded layers. Additional difficulty in the III-V to Si integration is the difference in the thermal expansion coefficients of the materials. It causes the build-up of stress in the bonded layers during the high-temperature processing steps, and can result in the formation of dislocations if the thermal strain exceeds the critical value [1, 2].

We have developed a platform, where 250 nm InP as the III-V layer on Si/SiO₂ substrate is used for fabrication of photonic crystal on-chip lasers with the buried heterostructure for the emission in 1550 nm wavelength range. The buried heterostructure separates the active material region, with layer(s) of either quantum wells or quantum dots in which the laser cavity is formed by the photonic crystal pattern, from the passive material region. This helps to avoid absorption losses and surface recombination outside the cavity. Evidently, large overlap between the active region and the high-*Q* cavity is necessary for the optimal laser performance. However, achieving the necessary overlap is challenging not only due to the required high-level alignment precision, but also because of possible expansion in the bonded device layer caused by the aforementioned differences in the thermal expansion coefficients.

In order to estimate the expansion of the bonded wafers locally, and its consequences for the alignment accuracy during the device fabrication, we have devised the following experiment. We defined a pattern of crosses with the electron beam (E-beam) lithography, transferred the pattern to the InP device layer using the dry etching, and then used E-beam as metrological SEM to estimate the changes in position for each cross after the pattern transfer.

Two different bonding approaches were taken to replicate the conditions during the fabrication of real devices. In case of the adhesive BCB (Benzocyclobutene)-based bonding, the crosses were first transferred to the InP wafer, which was then bonded to Si/SiO₂ in the wafer bonder at 250°C, and finally the crosses were opened from the other side by removing the InP substrate and the etch-stop layer (the equivalent of the double-sided processing). The metrological measurements show significant non-uniform distortion in the bonded InP layer observed as changes in the positions of crosses. It explains the substantial misalignment that appears between the buried heterostructure and the photonic crystal cavity in the fabricated laser, and its detrimental effect for the device performance. In case of the direct bonding approach, a thin ALD Al₂O₃ layer was deposited on both InP and Si/SiO₂ wafers before placing them on top of each other for pre-bonding [3]. The wafers were then thermally annealed in the wafer bonder at 300°C, and after the removal of InP substrate and the etch-stop layer the transfer of crosses was performed on already bonded sample (the equivalent of the single-sided processing). Additional high-temperature annealing at 650°C was used in between metrological measurements to examine the influence of the regrowth steps during the real device fabrication on the wafer expansion. The results agree with the alignment observed in the laser fabricated on the directly bonded wafer, and indicate the possibility to readily increase the accuracy further.

In conclusion, the successful integration of high-performance and efficiency InP photonic crystal lasers with the buried heterostructure on Si platform relies both on the high-precision alignment and the level of control of the expansion in the device layer of the bonded wafer. Careful consideration of these elements and successive planning of the fabrication process flow is necessary in order to achieve the optimal device performance.

[1] D. Pasquariello et al., "Crystalline Defects in InP-to-Silicon Direct Wafer Bonding", *Jpn. J. Appl. Phys.* **40**, 4837 (2001).

[2] T. Fujii et al., "Epitaxial growth of InP to bury directly bonded thin active layer on SiO₂/Si substrate for fabricating distributed feedback lasers on silicon", *IET Optoelectron.* **9**(4), 151 (2015).

[3] H. K. Sahoo et al., "Low temperature bonding of heterogeneous materials using Al₂O₃ as an intermediate layer", *J. Vac. Sci. Technol. B* **36**(1), 011202 (2018).